

## **Utilization of Fine Coal in FETC GranuFlow Products for Pulverized Coal Firing**

Mark C. Freeman (mfreeman@fetc.doe.gov, 412/892-6294)

Carl P. Maronde (maronde@fetc.doe.gov, 412/892-6246)

Federal Energy Technology Center

Gary F. Walbert (gwalbert@fetc.doe.gov, 412/892-5764)

Parsons Power Group, Inc.

### **Summary**

Industrial-scale pulverization and pilot-scale combustion assessments of coal feeds treated by the GranuFlow Process were performed at the Federal Energy Technology Center (FETC) to determine their initial suitability for utilization in coal-fired utility boilers. The GranuFlow Process is a newly-patented technology designed to improve the dewatering and handleability of fine-size coal through the addition of an Orimulsion™ or asphalt-based emulsion prior to dewatering.

Three coal feeds -- one with conventionally-dewatered fines and two with GranuFlow-treated fines -- were produced in FETC's Coal Preparation Process Research Facility (PRF) using a Pittsburgh seam parent coal. The first test coal consisted of a blend of 20% conventionally dewatered fines back mixed with 80% coarse coal. The second and third test coals consisted of blends of 20% GranuFlow-treated fines/80% coarse coal and 40% GranuFlow-treated fines/60% coarse coal, respectively. Pulverization and combustion tests were then conducted on all three coal products.

Both GranuFlow products were successfully fed through a Williams Pulverizer, a roller-type mill that is used in industrial pulverized coal-fired facilities. Short-duration tests showed no difficulty in achieving the desired particle size distribution (i.e., about 70% minus 200 mesh) and moisture content (less than 2 wt%) using a typical mill outlet temperature of 150-160°F.

Combustion testing in FETC's Combustion and Environmental Research Facility (CERF) showed only small differences in fly ash loss-on-ignition and emissions between the baseline parent coal and the GranuFlow products over a wide range of burner conditions. Some reduction in early combustion/coal reactivity was observed with the GranuFlow products at CERF furnace residence times of about 0.9 second, although these differences were much less at the longer residence times associated with utility power plants.

In short, these preliminary results indicate that GranuFlow products should be considered feasible for pulverized coal applications. Successful pulverizer and combustion tests were achieved at a higher percentage of treated coal fines (20% and 40%) than what would normally be available for conventional coal cleaning, where only 5-10% of coal typically reports as fines. Consequently, it is expected that even less differences in pulverizer and combustion performance would be observed between parent coals and commercial GranuFlow products.

## **Background**

Estimates place the quantity of coal in U.S. waste piles at 2-3 billion tons, which is quite significant given the current U.S. coal production of about 1 billion tons/yr. Much of this material is very moist, fine coal (minus 28 mesh) that cannot be readily handled and included in the variety of products from commercial coal preparation plants. This wet fine coal waste amounts to about 50 million tons/year, as about 5-10% of commercial coal preparation product reports as a wet, fine (minus 28-mesh) coal which cannot be back mixed with coarser sizes. Typical utility grades are very coarse, with a specified topsize in the 2- to 6-inch range, while other products (e.g., stoker coal double-screened at 1- to 1.5-inch by 1/4-inch, less than 15% minus 1/4-inch) have strict tolerances on fines content.

Researchers in FETC's Office of Science and Technology have developed and patented the GranuFlow Process for treating fine-size coal to improve its dewatering and handling characteristics (1-5). This GranuFlow Process entails the addition of a small amount (typically 2-8 wt%) of Orimulsion<sup>TM</sup>, which consists of 70 wt% bitumen oil emulsified in 30 wt% water, or similar asphalt-based emulsions to a coal-water slurry prior to dewatering. The Orimulsion<sup>TM</sup> coats the surface of the coal particles increasing their hydrophobicity which, in turn, improves dewatering. More importantly, the dewatered product consists of small-size, micro agglomerates that give the product a granular appearance and a much more free-flowing characteristic with improved handling characteristics, including increased freezing resistance. These micro agglomerates also attract dust particles, which considerably lowers the product dustiness (1).

The GranuFlow Process was developed in response to coal producer needs to more fully exploit the fines portion of their preparation plant products that typically have been discarded because of high-moisture contents and poor handleability. Consequently, producers could recover additional quantities of marketable coal from their mine outputs and/or improve the overall quality of their products by crushing all or part of the coal to liberate additional impurities prior to more extensive cleaning of the subsequent finer-size plant feeds.

With the successful completion of work both at FETC and in the field to establish the performance and operability of the GranuFlow Process, an effort was needed to examine GranuFlow products from the standpoint of utilization. This experimental test program was developed to make an initial assessment of GranuFlow-treated coal products in terms of the potential impacts to pulverization and combustion operations at coal-fired utilities. This study was specifically aimed at assessing the baseline performance of GranuFlow-treated products prior to future large-scale or full-scale tests, and to assist in the marketing the GranuFlow Process to commercial coal preparation plants and utilities.

## **Approach**

The approach involved the preparation of three batches of feed coal -- one with conventionally treated fines and two with GranuFlow-treated fines -- that were subjected to pulverization and combustion tests. The first test coal, designated as the parent coal product, contained a mix of 80% untreated coarse coal and 20% untreated fine coal. The second test coal, designated as the 20% GranuFlow product, contained a mix of 80% untreated coarse coal and 20% GranuFlow-

treated fine coal. The third test coal, designated as the 40% GranuFlow product, contained a mix of 60% untreated coarse coal and 40% GranuFlow-treated fine coal. The parent coal provided the baseline pulverization and combustion data to enable performance comparisons with the GranuFlow-treated coals.

The selection of 20% and 40% GranuFlow-treated fines was made to test the upper limits of fuel handling, pulverization, combustibility, and emissions issues. Because actual commercial coal preparation plants have fine coal (28 mesh by zero) by-products that typically amount to 5-10% of the coarse coal, one would expect that commercialized GranuFlow products would contain lower percentages of GranuFlow-treated fines than used in this study. However, in this initial evaluation, it was felt that showing the viability of the GranuFlow Process at high levels of treated fines would allow for any pulverization and combustion differences to be more readily observed, while providing greater comfort to potential industry users.

### **Experimental Facilities**

Three separate test facilities at FETC were used in the performance of this work -- the Coal Preparation Process Research Facility (PRF), the Williams Company Roller Mill Pulverizer, and the Combustion and Environmental Research Facility (CERF).

The three test coals were produced in the FETC PRF, a pilot-scale unit with conventional coal handling, cleaning (e.g., cyclones), and dewatering equipment that would be found at commercial coal preparation plants. In addition, the PRF has an internal circuit for the study of advanced coal beneficiation processes to significantly reduce mineral matter and sulfur content. This circuit is particularly suited for fine coal, as three deep-cleaning processes have been evaluated for outside organizations. The PRF can integrate its full circuit for coal handling and conventional coal cleaning with its area for advanced coal beneficiation processes, such as advanced froth flotation, heavy-media cyclones, and fine coal dewatering.

Pulverization tests were performed in FETC's 1 ton/hr Williams Company Roller-Mill Pulverizer facility. Williams Company pulverizers are commercially sold for industrial-scale, pulverized-coal burners up to 30 million Btu/hr. The FETC Williams Pulverizer facility is a complete system for pulverizing, drying, and recovering coal down to 70-80% minus 200 mesh. The facility includes a feed coal storage bin, screw feeder, roller mill, spin separator, cyclone separator, cyclone fan, dust collector, dust collector fan, and oil-fired heater. The Williams Pulverizer is configured for indirect firing, with discharge of the mill outlet (containing pulverized coal) to a storage bin. The mill transport gas is derived from a fuel oil burner to achieve the proper ranges of mill inlet temperature and oxygen content. A FETC-designed pressurized nitrogen transport system uses a simple venturi eductor to convey the pulverized coal into storage bins for the FETC pilot-scale combustion units.

Combustion testing of the three test coals was accomplished in the CERF. The CERF is FETC's principal state-of-the-art facility that is used to assess the performance of solid, liquid, and gaseous fuels in typical pulverized/suspension-fired systems, including the capability to co-fire multiple fuels. Commissioned in 1989, the basic design criteria for the 500,000 Btu/hr CERF achieves similarity with full-scale utility and industrial boilers. Using past experience at FETC

and elsewhere with pilot-scale combustion rigs, the CERF was designed to closely duplicate typical full-scale specification ranges for burner relative mass flow (fuel and air) and velocities, furnace temperature distributions, radiant furnace gas residence time, and convective section gas velocity.

Although pilot-scale combustors, such as the CERF, cannot exactly duplicate conditions in full-scale units, they have proven to be useful in obtaining information on the integrated effects of a number of interdependent design and operating variables. Fuel quality is assessed by comparing its pilot-scale performance with that of reference fuels for which full-scale performance is known.

Figure 1 presents an isometric layout of the CERF. The facility is highly automated and equipped with a state-of-the-art personal-computer-based data acquisition and process control system. The main components of the CERF include:

- o vertically down-fired refractory-lined combustion chamber
- o refractory-lined transition section
- o refractory-lined horizontal convective section
- o solid fuel preparation, storage, and transport systems
- o liquid fuel storage and transport system
- o natural gas supply system
- o IFRF-type movable block variable swirl burners (conventional and low- $\text{NO}_x$ )
- o gas injection panel for air, steam,  $\text{CO}_2$ , CO,  $\text{N}_2$ , other gases ( $\text{H}_2$ ,  $\text{NH}_3$ ,  $\text{NO}_x$ )
- o pulse-jet baghouse for particulate control

The CERF is equipped to evaluate the following fuel characteristics: (1) transport, handling and storage; (2) combustibility, including flame stability and carbon conversion efficiency; (3) ash deposition rates, deposit heat transfer properties such as emissivity and thermal conductivities, and deposit removal characteristics under soot-blowing requirements; and (4) flue gas emissions, such as  $\text{SO}_2$ ,  $\text{NO}_x$ , CO, total hydrocarbons, and particulates.

Prior pulverized coal-fired CERF testing consists of about twenty coals, including run-of-mine, conventionally washed, and deep-cleaned coals, along with various coal blends. The CERF has also been used to evaluate co-firing of various fuels, including biomass wastes, such as sawdust, and energy crops, such as switchgrass.

### **Test Coal Preparation**

The feed coal for this test program was a Pittsburgh seam coal obtained from the Monview Mine. As the coal was being processed in the PRF, incremental on-line samples were collected to provide the feed coal characteristic data, including ash, total sulfur, heating value, and Hardgrove Grindability Index (HGI).

The entire 10-ton lot was crushed to a nominal 3/4-inch topsize in the PRF. Approximately 7.5 tons were loaded out and delivered to an off-site coal storage facility as the coarse coal product. This crushed coal was used as the source for the coarse coal fractions for each of the three test

coals. As this coarse coal product was being prepared, samples were collected for particle size distribution analysis which is reported in Table 1. The moisture content of the as-delivered coarse coal product was 3.0 wt%.

Table 1. Particle Size Distributions for Coarse and Fine Feed Fractions and the Three Final Test Coals

Particle Size Range	Feed Fractions (Actual)		Test Coals (Estimated)		
	Coarse Feed Fraction	Fine Feed Fraction	Parent Coal	20% GranuFlow Product	40% GranuFlow Product
Plus 1/2"	20.2	---	16.9	16.3	12.3
1/2" x 1/4"	38.4	---	32.1	30.9	23.6
1/4" x 8 mesh	19.7	---	16.5	15.9	12.0
8 x 30 mesh	11.8	---	9.9	9.5	7.2
30 x 50 mesh	5.2 <sup>1</sup>	9.9	6.0	6.3	7.0
50 x 100 mesh	2.5 <sup>1</sup>	24.5	6.1	6.7	11.0
100 x 200 mesh	1.3 <sup>1</sup>	22.8	4.8	5.4	9.7
200 x 325 mesh	0.6 <sup>1</sup>	11.1	2.3	2.6	4.7
Minus 325 mesh	0.3 <sup>1</sup>	31.7	5.4	6.4	12.5

<sup>1</sup>Estimated distribution based on 9.9% of total coarse fraction passing 30 mesh.

The remaining 2.5 tons of 3/4" x 0" coal in the PRF was used to prepare the untreated and GranuFlow-treated fines products. The processing scheme used to prepare these fines products included pulverization in the PRF hammermill to produce a nominal 28-mesh topsize product, and preparation of this 28 mesh x 0 coal into a coal-water slurry at 20% solids concentration. This slurry was then pumped to a 6-inch Bird screen-bowl centrifuge for dewatering to produce the final fines products. Prior to dewatering, samples of the pulverized 28 mesh x 0 coal were collected for particle size distribution and are reported in Table 1.

The first portion of coal delivered to the PRF's Bird centrifuge was processed without any additives to produce 740 pounds of untreated dewatered coal fines at an analyzed moisture content of 23.7 wt%. Production of the GranuFlow-treated fines was then initiated with Orimulsion<sup>TM</sup> additive to the coal-water slurry at an 8% weight ratio of bitumen to coal prior to dewatering in the centrifuge. This portion of the production run generated approximately 4500 pounds of GranuFlow-treated fines at an analyzed moisture content of 20.6%. The addition of Orimulsion<sup>TM</sup> to the feed slurry was very simple, using a small metering gear pump for direct injection at a point approximately 20 feet upline from the centrifuge. This provided adequate mixing from the turbulent action as the slurry flowed through the line.

These untreated and GranuFlow-treated fines products were transported to an off-site facility for blending with the coarse coal product to produce the final three test coals. The test coals were prepared by first weighing out exact portions of each of the required coarse and fine fractions.

Each test coal was prepared by placing portions of the coarse and fine fractions in a layering fashion to create a single pile. Coning and long-piling techniques were then used to thoroughly homogenize each test coal. The blending operation was done as quickly as possible to preserve the moisture content in each test coal. Following the blending and homogenization process, each test coal was covered and stored until the pulverization tests.

Table 2 presents the preparation results of the three test coals. Actual particle size determinations were not made because of difficulties with screening at the finer sizes as a result of particle agglomerating effects which were likely due to the presence of Orimulsion<sup>TM</sup>-coated particles. However, estimated particle size distributions of each test coal were calculated based on the actual percentages of coarse and fine fractions that were used to formulate the test coals.

Table 2. Test Coal Blend Weights and Moisture Contents

	Untreated Coal		GranuFlow Coal #1		GranuFlow Coal #2	
	<i>As-Rec'd</i>	<i>Dry</i>	<i>As-Rec'd</i>	<i>Dry</i>	<i>As-Rec'd</i>	<i>Dry</i>
Coarse Fraction Weight <sup>1</sup>	3000 lbs	2910 lbs	4800 lbs	4656 lbs	3600 lbs	3492 lbs
Fine Fraction Weight <sup>2</sup>	740 lbs	565 lbs	1400 lbs	1112 lbs	2800 lbs	2223 lbs
Total Test Coal Weight <sup>3</sup>	3740 lbs	3475 lbs	6200 lbs	5768 lbs	6400 lbs	5715 lbs
Percent Fine Fraction in Test Coal	24.7%	16.2%	22.6%	19.3%	43.7%	38.9%
Actual Weight of Test Coal Delivered to Pulverizer	3680 lbs	3477 lbs	6064 lbs	5730 lbs	6060 lbs	5521 lbs
Actual Moisture of Test Coal as Delivered to Pulverizer	5.5%	NA	5.5%	NA	8.9%	NA

<sup>1</sup> Dry weights for coarse fraction based on 3.0% moisture

<sup>2</sup> Dry weights for fine fractions based on 23.7% moisture in untreated fines fraction and 20.6% moisture in GranuFlow-treated fines fraction

<sup>3</sup> Total blend weight is sum of coarse and fine fraction weights

## Pulverization Test Results

The pulverization characteristics of the three test coals were assessed using the Williams Pulverizer. The primary objectives of this testing were to evaluate the handleability issues, including coal discharge from the feed bin to the pulverizer's screw feeder and roller-mill, and to quantify any effects on the overall pulverizer operation. It was felt that a successful test in FETC's Williams Pulverizer would be relevant to utility-type pulverizers based on some similarity in design concepts and fracture mechanisms. Conversely, any major trouble in the

Williams Pulverizer operation with GranuFlow products - such as particle accumulation and sticking to the rollers - would have signaled immediate concern before contemplating any large-scale tests.

During pulverization tests, the inlet air temperature to the mill was set to maintain a mill exit gas temperature of 150° F. The pulverizer was adjusted (e.g., spin classifier speed) with the objective of producing typical pulverized-coal grind for bituminous coals, with about 70% passing 200 mesh (74 microns). Feed coal HGI and moisture data were provided to set the operating conditions of the pulverizer system.

Because this study was the first technical evaluation of the fuel handling and combustion of GranuFlow product, a conservative approach was adopted to evaluate feasibility within limited labor and materials resources. For example, limiting the duration of the Williams Pulverizer operations resulted in considerable savings in GranuFlow product fuel preparation and disposal costs for products not used in combustion tests, given the small-scale (33 lb/hr) of the CERF.

Therefore, a short pulverization test run of only two hours was planned for the parent coal as no difficulties in processing about 3000-3500 lbs of feed coal. A two-hour test period was determined to be long enough to generate the needed pulverizer operational data. However, for the two test coals containing GranuFlow-treated fines, longer pulverization test runs were planned to generate more operational data, particularly to evaluate the potential for the buildup of residues on the internal mill components. These longer test runs of about 4-5 hours were estimated to require over 6,000 lbs of each test coal.

Each test coal was delivered to the Williams feed bin just prior to testing. As each test coal was transferred from the truck to the feed bin, ten incremental samples of 5 pounds each were collected and analyzed for moisture. This information was then immediately provided to the Williams operators for establishing pulverizer settings.

Each Williams Pulverizer test run included both a pre- and post-test inspection and cleaning of the feed bin, screw feeder, and roller-mill. Evidence of the buildup of any material was noted, and photographs were taken, prior to cleaning at the conclusion of each pulverized coal test.

The principal measures of the pulverization characteristics of the three coals was the final product particle size distribution and coal feed rate to the mill. The coal feed rate to the pulverizer was used as the most important performance measure because the final product particle size may not be the best indicator of the ease of pulverizing as an integral spin separator (i.e., classifier) returns any oversize particles to the mill for regrinding.

The raw coal feed rate is controlled by the differential pressure across the mill. As particles are discharged from the mill, this pressure differential drops and feed is increased to the mill. Because oversize particles are returned to the mill via the spin separator, this effectively reduces the available raw coal feed. Thus, a good indicator of the grindability of the coals can be determined by the raw coal feed rate or the product discharge rate from the mill.

At the end of each pulverization run for the three test coals, the pulverized-coal product was removed from the collection bin by a vacuum truck for disposal. During the discharge of each test coal from the pulverizer collection bin, a total of four single-drum quantities of pulverized coal were collected at regular intervals to provide samples for size distribution and combustion testing. Final product particle size distributions were obtained from a composite sample (using a drum thief) from each of the four drums.

Table 3 highlights the Williams Pulverizer operational parameters and results for the parent coal and both GranuFlow products. Of note is that the Table 3 reported particle size distributions are based on a wet sieve. A considerable manual effort was required to work the GranuFlow products through screens at 100 and 200 mesh because of their propensity to adhere and blind the screens, presumably as a result of the light oil coating on particles from the Orimulsion<sup>TM</sup> treatment. Conventional dry sieving with Rototap equipment was not able to measure fine coal particles because of even stronger blinding effects.

Table 3. Pulverization Test Results

	Untreated Parent Coal	20% GranuFlow Blend	40% GranuFlow Blend
Test Duration, hr	2.0	3.2	2.4
Avg Coal Feed Rate, lb/hr	1739	1791	2300
Avg Mill Inlet Gas Temp, °F	629	655	736
Avg Mill Outlet Gas Temp, °F	168	155	150
Pulverized Coal Moisture Content,	1.45	1.26	1.40
Pulverized Coal Size Distribution,			
+ 50 Mesh	NA	0.0	0.0
+ 100 Mesh	NA	2.3	4.8
+ 200 Mesh	22.6	22.0	31.2
Minus 200 Mesh	78.4	78.0	68.8

Considering the short duration of operation, these tests were generally successful in producing the desired range of particle size distributions for the parent coal and GranuFlow products. Post-test inspection of the Williams Pulverizer internals revealed only minimal sticking and caking on some of the mill internal components in the case of the GranuFlow products, but this was not judged to potentially cause equipment damage or longer-term operational difficulties.

During pulverization, the moisture content was reduced to less than 2 wt% in all cases. This was very important outcome in the case of the GranuFlow products, indicating that proper drying was achieved at a constant mill outlet temperature of about 150-160°F. This was a major finding, given the initial concern that pulverizer performance might be inhibited, especially with such a high level (40%) of GranuFlow-treated product.

During the 40% GranuFlow Product test, several operational anomalies were observed. For example, the feed rate was unexpectedly high. Although the transport gas temperature was run at its maximum, it was somewhat difficult to maintain the 150°F mill exit gas temperature. This is believed to be directly caused by the higher moisture content of the feed, which was consistent with higher levels of steam observed in the exhaust duct discharge. In addition, the pulverized product was somewhat coarser.

There were some difficulties experienced in feeding the GranuFlow products from the 40-ton capacity overhead hopper to the pulverizer inlet. Some GranuFlow product that had adhered to the hopper walls and bridged at the conical discharge required manual attention to free blockages and allow continued pulverization. The 20% GranuFlow Blend exhibited this problem only during the last 500 lbs of feeding, while the 40% GranuFlow Blend exhibited this problem throughout the test. These difficulties may have resulted from the fact that the overhead hopper contained such a low inventory (< 5 tons) of GranuFlow product relative to its normal full capacity (40 tons). This low inventory obviously did not produce the usual pressure head on the hopper discharge. In addition, the FETC hopper design, in terms of conical discharge angle/dimensions and degree of vibration, are likely different from what is typically found in utility coal handling systems. Thus, while these difficulties are not viewed as insurmountable, they do need to be investigated at full-scale.

### **Coal Product Analyses**

Table 4 presents the standard proximate and ultimate analyses for the as-fired, pulverized parent coal and GranuFlow products that were used during CERF tests. These analyses are based on representative samples (e.g., five-point thief samples on drums) of pulverized coal.

As expected, Table 4 shows excellent agreement between the parent coal analyses and the two GranuFlow products. The presence of Orimulsion<sup>TM</sup> additive in the GranuFlow products is observed to have an insignificant effect on the product coal analyses. For example, only a slight increase in volatile matter content is observed with the GranuFlow products.

These results are consistent with the fact that the 20% GranuFlow product contained a net bitumen oil content of about 1.6 wt%, while the 40% GranuFlow product contained about 3.2 wt% bitumen oil. In a few instances, the slight differences in some Table 4 values and trends could be explained within the expected range of reproducibility, given sampling considerations.

Of note is that the parent Pittsburgh Seam coal is classified as a high-volatile "A rank" bituminous coal. This coal is typical of other U.S. eastern bituminous coals, with a moderate sulfur content of about 2.2 lb SO<sub>2</sub>/MMBtu, which is somewhat lower than other coals mined from the Pittsburgh seam. This parent Pittsburgh Seam coal is also slightly lower (about 20%) in nitrogen content relative to many other eastern U.S. bituminous coals.

Table 4. Proximate and Ultimate Analyses of  
Pulverized Parent Coal and GranuFlow Products

Coal Analyses	Untreated Parent Coal	20% GranuFlow Product	40% GranuFlow Product
Proximate (as-received wt%)			
Moisture	1.45	1.26	1.40
Volatile Matter	37.64	38.28	40.53
Fixed Carbon	53.81	52.78	51.38
Ash	7.10	7.70	6.70
Ultimate (dry wt%)			
Hydrogen	4.97	5.58	4.74
Carbon	78.76	78.25	79.26
Nitrogen	1.61	1.57	1.57
Sulfur	1.52	1.77	1.67
Oxygen	5.93	5.04	5.96
Ash	7.20	7.79	6.79
Heating Value (Btu/lb, as-rec'd)	13920	13913	14030
Heating Value (Btu/lb, dry)	14124	14089	14229
Lb SO <sub>2</sub> /MMBtu, equivalent	2.16	2.52	2.35
Lb NO <sub>2</sub> /MMBtu, equivalent	3.75	3.66	3.63
Ash Loading (lb/MMBtu)	5.10	5.53	4.77

### Combustion Test Operation

CERF tests were performed to obtain preliminary information on the GranuFlow products. This involved one day of testing for each fuel. Although the particle size distribution of the 40% GranuFlow product was somewhat coarser than the parent coal and the 20% GranuFlow product, it was felt that this variation would not be significant towards the primary CERF test objective to assess if significant differences exist with the GranuFlow products.

The CERF testing on all three coals utilized the standard, single-register variable swirl burner based on International Flame Research Foundation (IFRF) guidelines. The CERF burner is designed to accurately set the secondary air swirl number (swirl number, SN, is defined as the ratio of tangential momentum to axial momentum) over a range of 0-2.0 SN. Most pulverized coal-utility burners are designed to provide swirl numbers of less than 1.0 SN, owing to pressure drop and blower capacity considerations. The CERF burner is operated under standard conditions of 0.7 SN, and is normally adjusted in the 0.3-1.3 SN range.

All CERF tests were conducted under normal full load, which included a thermal firing rate of 465,000 Btu/hr that was achieved with about 33 lb/hr coal flow. In addition, all CERF tests were conducted with the standard 500°F secondary air preheat. Although most U.S. utility boilers use 300-350°F preheat levels, the typical value of 500°F for small pilot-scale combustors is used because of the higher radiative losses at the burner and the fact that the CERF primary air is unheated.

For each test coal, the CERF standard burner conditions of 20% total excess air (XSA) were first established with a 0.7 secondary air swirl number and a primary air/secondary air ratio (PA/SA) of about

0.25. Flame stability and combustibility was then assessed from this point by adjusting secondary air swirl (0.3, 0.7, 1.3), excess air (10%, 20%), and primary/secondary air ratio for a total of six different burner conditions to compare fuels in short duration tests. Table 5 summarizes the sequential burner test conditions performed for each fuel.

Table 5. CERF Burner Conditions for Short Duration Combustibility Tests

Test	% Excess Air (XSA)	Secondary Air Swirl Number (SN)	Primary/Secondary Air Ratio (PA/SA)
1	20	0.7	0.25
2	20	0.7	0.20
3	20	0.7	0.30
4	20	1.3	0.25
5	20	0.3	0.25
6	10	0.7	0.30

After steady conditions were achieved for all six burner conditions, the usual CERF characterizations were performed. This included the flame root position, flue gas emissions, and combustibility (burning profiles) over a 30-minute period.

The flame position was measured by inserting a thermocouple through the natural gas pilot tube and into the center of the burner quarl. The thermocouple is inserted to a point where it reads 1800°F, and the flame root position is defined as this distance from the burner pipe exit. Typically, measured flame root positions will vary from about 2 to 10 inches, depending upon the coal reactivity (e.g., factors such as rank) and burner conditions.

Flue gas emissions were continuously monitored with standard process gas analyzers based on infrared spectroscopy (SO<sub>2</sub>, CO, CO<sub>2</sub>), chemiluminescence spectroscopy (NO<sub>x</sub>), and paramagnetic properties (O<sub>2</sub>). These analyzers were calibrated with a zero gas and known span gas, with a second, mid-span calibration gas as a check. Flue gas sample was continuously withdrawn, near the ultrasonic flow metering system, and conditioned with a sintered metal filter and ice-bath to remove particulate and moisture before the process gas analyzers. Data was recorded every 30 seconds so running averages could be determined during test periods.

Combustibility data was obtained from simultaneous 30 minute, high-volume sampling at three CERF locations - Section 3 and Section 5 in the CERF's radiant furnace, and the baghouse inlet. This simultaneous sampling helps establish the coal burning profile as particles proceed through the radiant furnace. These high-volume particulate samples were then analyzed using the ASTM procedures for moisture and ash content. Combustion efficiencies were then determined by mass balance using the ash analyses of the particulate samples and the coal's original ash content.

## Combustion Test Results

No problems were observed in the CERF's coal feeding/transport system with either GranuFlow product. Coal feed rate stability and variation in flue gas O<sub>2</sub> content were not indicative of any unusual occurrences with the GranuFlow products.

Table 6 provides the six-test average and range results for the parent coal and GranuFlow products in terms of loss-on-ignition (LOI) for particulate samples, combustion efficiency, flame root position, and flue gas emissions.

Table 6. CERF Six-Test Average and Ranges for Parent Coal and GranuFlow Products

	Average of Six Tests			Range of Six Tests		
	Parent Coal	20% GranuFlow	40% GranuFlow	Parent Coal	20% GranuFlow	40% GranuFlow
Combustion Profiles, Particulate Sampling						
% LOI Section 3	16.2	37.4	31.6	10.5 - 31.3	15.4 - 50.5	22.1 - 47.4
% LOI Section 5	4.0	4.1	2.9	1.2 - 9.2	1.1 - 8.2	1.1 - 5.8
% LOI Baghouse Inlet	6.1	7.1	7.6	4.6 - 8.2	5.4 - 9.5	6.1 - 11.1
Combustion Efficiency,						
Section 3	98.4	94.5	96.5	96.5 - 99.1	91.4 - 98.5	93.5 - 97.9
Section 5	99.7	99.6	99.8	99.2 - 99.9	99.2 - 99.9	99.6 - 99.9
Baghouse Inlet	99.5	99.4	99.4	99.3 - 99.6	99.1 - 99.5	99.1 - 99.5
Flame Root Position,	3.4	3.2	3.7	2.0 - 4.5	2.0 - 4.9	2.3 - 4.8
Emissions, dry basis						
O <sub>2</sub> (%)	4.23	4.26	4.35	2.9 - 4.6	3.2 - 4.6	3.4 - 4.6
CO <sub>2</sub> (%)	14.58	14.34	14.28	14.2 - 15.8	14.1 - 15.3	14.0 - 15.1
SO <sub>2</sub> (ppm)	1058	1046	1040	1016 - 1058	1002 - 1180	998 - 1115
NO <sub>x</sub> (ppm)	525	441	491	442 - 697	303 - 658	341 - 670
CO (ppm)	22	34	21	20 - 24	28 - 37	18 - 25
Emissions, lb/MMBtu						
SO <sub>2</sub>	2.15	2.16	2.13	2.07 - 2.19	2.09 - 2.29	2.07 - 2.22
NO <sub>x</sub>	0.77	0.66	0.72	0.61 - 1.03	0.46 - 0.76	0.59 - 1.00

Some trends are evident in Table 6. The reduced LOI from Section 3 (about 0.9 seconds of gas residence time) and Section 5 (about 1.6 seconds of gas residence time), is consistent with the expected burning profiles.

Table 6 indicates that the six-test sequence for adjusting burner conditions did impact the flame characteristics for the parent coal and GranuFlow products. Specifically, the flame root position was altered significantly over the range of 2-5 inches, and the burning profiles (LOI and combustion efficiency) and NO<sub>x</sub> emissions were also altered over a wide range.

The burning profiles show that the GranuFlow products appear to be somewhat less reactive than the parent coal in the CERF's upper section at low gas residence times (Section 3). However,

Section 5 and baghouse inlet measurements indicate similar combustion between the parent coal and the GranuFlow products. Specifically, only a slight increase (less than 2%) in baghouse inlet LOI was observed in most cases for the GranuFlow products versus the parent coal.

Final combustion efficiencies were over 99% (99.1-99.9% range) in all cases, as measured in Section 5 and baghouse inlet. The six-test baghouse inlet average of 99.5% for the parent coal was nearly identical to the six-test average of 99.4% for both GranuFlow products. The reduction in early combustion can be seen with the 20% and 40% GranuFlow products, with a six-test average of 94.5% and 96.5% (Section 3), respectively, versus the parent coal value of 98.4% in Section 3.

Flue gas emissions were similar between the GranuFlow products and the parent coal. As expected, SO<sub>2</sub> emissions were nearly identical in the 2.1-2.3 lb/MMBtu range for the six tests, and close to the 2.2-2.5 lb/MMBtu calculated values that are based on the coal analyses shown in Table 4. CO emissions were less than 40 ppm (dry basis) for all tests, which is indicative of good combustion.

NO<sub>x</sub> emissions ranged from 0.5-1.0 lb/MMBtu over the study as a result of varied burner operation. This was intended, and the consequence of varying flame root positions. For example, lowering secondary air swirl and/or increasing the primary air/secondary air ratio has the effect of increasing the flame root position. In general, for a given coal, CERF NO<sub>x</sub> emissions will increase considerably if the flame root position increases (i.e., moved off the burner) as a result of various burner adjustments. During this study, observed NO<sub>x</sub> emissions were very similar to other eastern U.S. bituminous coals that have been tested in the CERF.

Slight differences in NO<sub>x</sub> emissions were observed between the parent coal and the GranuFlow products which was consistent with typical CERF results. Consequently, while the GranuFlow products show somewhat lower NO<sub>x</sub> emissions than the parent coal, these differences are not really significant as they are well within the range that could be compensated with additional adjustment of burner operation.

In comparing in-furnace (Sections 3 and 5) and baghouse inlet values, several points should be made beyond the usual analytical considerations and the fact that this sampling is not isokinetic. First, the relative quench times between the in-furnace sampling (from water-cooled probes) is not the same as the cooling that actually occurs for particles that leave the radiant furnace and enter the convective pass and the baghouse. In addition, Section 3 and 5 sampling is performed at the furnace centerline, where the diameter is about 19 inches. Also, some (about 20%) of the furnace ash reports as bottom ash (before the convective section), and thus never reaches the baghouse. Because the CERF's bottom ash hopper is hot, particles can continue to burn, resulting in a bottom ash with essentially no unburned carbon. Thus, apparent combustion efficiencies based solely on the baghouse will be slightly lower than that in the furnace (i.e., Section 5) because of the difficulties in obtaining bottom ash in short-duration tests.

To examine combustion test data in more detail, Table 7 summarizes CERF results for the first three burner conditions, comparing the parent coal with both GranuFlow products, while Table 8 summarizes results for the last three burner conditions.

Table 7: CERF Results for First Three Conditions with Parent Coal and GranuFlow Products

	Test Condition No. 1			Test Condition No. 2			Test Condition No. 3		
	SN 0.7 XSA 20% PA/SA 0.25			SN 0.7 XSA 20% PA/SA 0.20			SN 0.7 XSA 20% PA/SA 0.30		
<i>Combustion Profiles, Particulate Sampling</i>	Parent Coal	20% Granu Flow	40% Granu Flow	Parent Coal	20% Granu Flow	40% Granu Flow	Parent Coal	20% Granu Flow	40% Granu Flow
% LOI in Section 3	10.7	50.5	30.2	18.2	46.4	22.1	10.5	27.8	26.4
% LOI in Section 5	2.0	4.6	2.3	6.8	8.2	1.1	2.2	2.2	2.9
% LOI in Baghouse Inlet	6.9	8.9	6.8	6.6	6.2	6.2	4.6	5.4	6.1
<i>Combustion Efficiency, %</i>									
Section 3	99.1	91.4	96.9	98.3	92.7	97.9	99.1	96.7	97.4
Section 5	99.8	99.6	99.8	99.4	99.2	99.9	99.8	99.8	99.8
Baghouse Inlet	99.4	99.2	99.5	99.5	99.4	99.5	99.6	99.5	99.5
<i>Flame Root Position, inch</i>	3.3	2.6	3.8	2.0	2.0	2.3	3.8	3.1	4.6
<i>Emissions, dry basis</i>									
O <sub>2</sub> (%)	4.60	4.56	4.51	4.58	4.45	4.57	4.54	4.49	4.56
CO <sub>2</sub> (%)	14.21	14.05	14.17	14.29	14.20	14.09	14.24	14.17	14.18
SO <sub>2</sub> (ppm)	1016	1002	1024	1058	1013	998	1045	1024	1029
NO <sub>x</sub> (ppm)	514	430	430	442	385	578	560	500	500
CO (ppm)	23	28	19	22	33	18	21	37	19
<i>Emissions, lb/MMBtu</i>									
SO <sub>2</sub>	2.14	2.15	2.12	2.19	2.11	2.07	2.17	2.14	2.12
NO <sub>x</sub>	0.77	0.65	0.65	0.66	0.59	0.86	0.83	0.75	0.74

Table 8: CERF Results for Last Three Conditions with Parent Coal and GranuFlow Products

	Test Condition No. 4			Test Condition No. 5			Test Condition No. 6		
	SN 1.3 XSA 20% PA/SA 0.25			SN 0.3 XSA 20% PA/SA 0.25			SN 0.7 XSA 10% PA/SA 0.25		
	Parent Coal	20% Granu Flow	40% Granu Flow	Parent Coal	20% Granu Flow	40% Granu Flow	Parent Coal	20% Granu Flow	40% Granu Flow
<i>Combustion Profiles, Particulate Sampling</i>									
% LOI in Section 3	8.7	40.3	39.9	18.0	15.4	25.9	31.3	43.8	45.2
% LOI in Section 5	2.5	2.3	NA	1.2	1.1	2.2	9.2	6.4	5.8
% LOI in Baghouse Inlet	5.2	6.5	7.6	5.2	6.2	7.6	8.2	9.5	11.1
<i>Combustion Efficiency, %</i>									
Section 3	99.3	94.3	95.2	98.3	98.5	97.5	96.5	93.4	94.0
Section 5	99.8	99.8	NA	99.9	99.9	99.8	99.2	99.4	99.6
Baghouse Inlet	99.6	99.4	99.4	99.6	99.4	99.4	99.3	99.1	99.1
<i>Flame Root Position, inch</i>	3.4	3.0	2.8	4.5	4.9	4.8	3.5	3.9	3.8
<i>Emissions, dry basis</i>									
O <sub>2</sub> (%)	4.43	4.50	4.64	4.39	4.40	4.50	2.88	3.16	3.41
CO <sub>2</sub> (%)	14.44	14.12	14.00	14.46	14.22	14.16	15.82	15.26	15.10
SO <sub>2</sub> (ppm)	1060	1024	1053	1010	1006	1021	1161	1180	1115
NO <sub>x</sub> (ppm)	487	303	341	697	658	670	452	369	425
CO (ppm)	20	34	23	21	37	23	24	32	25
<i>Emissions, lb/MMBtu</i>									
SO <sub>2</sub>	2.18	2.20	2.20	2.07	2.09	2.11	2.18	2.29	2.16
NO <sub>x</sub>	0.72	0.46	0.51	1.03	0.98	1.00	0.61	0.51	0.61

In the first three burner tests, the primary air flow (PA) was adjusted, while maintaining constant total excess air (XSA), to vary the primary air/secondary air ratio (PA/SA), in order to alter the

flame root position. In general, high PA flow (high PA/SA) tends to increase flame root position and NO<sub>x</sub> emissions. In the last three conditions, excess air (XSA) and secondary air swirl number (SN) were adjusted. In general, low XSA tends to increase LOI and reduce NO<sub>x</sub> emissions, while low SN tends to increase both the flame root position and NO<sub>x</sub> emissions.

In viewing Tables 6-8, it is noteworthy that the reported sampling is well downstream of the combustor, and at the flue gas meter location before the baghouse. Consequently, the furnace O<sub>2</sub> content would be about 1% lower than the reported values based on the weekly mass-balance checks of air in-leakage into the radiant combustor.

Flame stability was achieved under all six burner conditions with the parent Pittsburgh seam coal and both GranuFlow products. The normal flame root position was measured at about 2-3 inches, and similar to other U.S. eastern bituminous coals that have been tested in the CERF. Under conditions of low swirl (Test Condition No. 5) and high primary air flow (Test Condition No. 3), the flame root position increased as expected. Because the burner quarl extends about 4.5 inches from the coal pipe exit, flame root positions from 3-6 inches represent well-anchored flames. The flame root position affects flame stability because it relates to the amount of heat transfer back to the burner quarl. Thus, the tracking of the refractory temperatures in the burner quarl and top combustor section verified the flame stability.

In viewing each of the six conditions reported in Tables 7 and 8, there is general agreement between the parent coal and the GranuFlow products. As discussed above, one exception was the upper furnace (Section 3) combustion where the GranuFlow products were observed to exhibit higher Section 3 LOI than the parent coal.

In general, particulate samples taken in Section 3 (closest to the flame) exhibit the highest unburned carbon and the most variability. This variability is also related to the ability to consistently quench the burning coal particles as they are drawn through the high-volume sampling probe, which contains a sintered metal filter assembly inside a water cooled jacket. Consequently, the variance in the net gas suction rate can influence the quenching and thus, the apparent level of LOI in the collected sample, as discussed above.

Flame stability was shown with the parent Pittsburgh seam coal and both GranuFlow products. The parent Pittsburgh seam coal was not found to be among the most reactive coals tested in the CERF, with unburned carbon (i.e., loss-on-ignition) in baghouse fly ash samples that was in the 6-10 wt% range over a variety of burner conditions. However, this allowed for practical comparison with the GranuFlow products.

Combustibility results were comparable at the longer furnace residence times, although the GranuFlow products were somewhat less reactive at short furnace residence times near the flame region. The CERF results show additional combustion for the GranuFlow products, relative to the parent coal, between 1 and 1.6 seconds of residence time. In most tests, a slight increase in baghouse inlet LOI was exhibited with the GranuFlow products relative to the parent coal.

At this point, it is difficult to conclusively explain the slight differences in combustion between the GranuFlow products and the parent coal, as several factors could be operative. These factors include the slightly coarser particle size distribution (Table 3) of the 40% GranuFlow product,

the short duration of tests, possible combustion effects from the Orimulsion™ coating, and the potential for particle reagglomeration in the CERF coal feeding system.

Because the CERF is an indirect-fired system (i.e., pulverization is separate from burner feed), one would expect even less differences for the direct-fired systems used in utility power plants. In direct-fired systems, bin storage and discharge of pulverized coal does not occur. Because utility pulverized-coal power plants are typically designed for 1 to 3 seconds of residence time, the CERF results do not appear problematic in terms of assessing likely power plant impacts on unburned carbon with the use of GranuFlow products.

Particularly important was that no dramatic decline occurred when burning the 40% GranuFlow product as compared to the 20% GranuFlow product. Clearly, combustion differences that were exhibited seem small when compared with the fact that the 40% GranuFlow product contains essentially twice the Orimulsion™ content as the 20% GranuFlow product.

In summary, the following points suggest that the CERF testing represented a stringent evaluation of GranuFlow products:

- The tested GranuFlow products had greater fractions (20% and 40%) of Orimulsion™-treated coal than what would be encountered in utility practice.
- Particle reagglomeration is not an issue for most utility power plants, unlike the CERF indirect-fired system, where reagglomeration was possible with pulverized-coal storage.
- The CERF combustion results after 1 second of gas residence time (a minimum value for utility boilers) showed only slight increases in LOI, even for 40% GranuFlow products.

## **Future Plans**

Additional industry input from commercial coal preparation plants and utilities will be sought to outline possible future experimentation beyond these early CERF tests. Clearly, additional CERF activities could compare different parent coals with GranuFlow products in order to cover a wider range of coal combustion reactivity, moisture contents, and grindability. Longer duration pulverization and combustion tests might also be helpful to more accurately determine minor differences between parent coals and GranuFlow products.

Demonstration of GranuFlow products in low-NO<sub>x</sub> burner systems should be included in any future plans. Typically, an increase in unburned carbon accompanies decreased NO<sub>x</sub> emissions as a result of the air/fuel staging that occurs in low-NO<sub>x</sub> burners. Because these CERF results did show reduced combustion at short residence times with the GranuFlow products, this could potentially lead to somewhat worse performance in low-NO<sub>x</sub> burner systems. A dual-register, low-NO<sub>x</sub> burner is available for the CERF that mimics the features of commercial low-NO<sub>x</sub> burners, and could be used for preliminary assessments of GranuFlow products.

## **Conclusions**

Overall, this testing indicates that GranuFlow products should be considered feasible from a technical perspective. Successful pulverizer and combustion tests were shown at higher GranuFlow utilizations - with 20% and 40% treated fine coal - than what would normally be available from conventional coal cleaning, where only 5-10% of coal typically reports as fines. Thus, these early pilot-scale results suggest that even less differences would exist between parent coals and GranuFlow products in future commercial applications.

Specifically, the key findings of this study are:

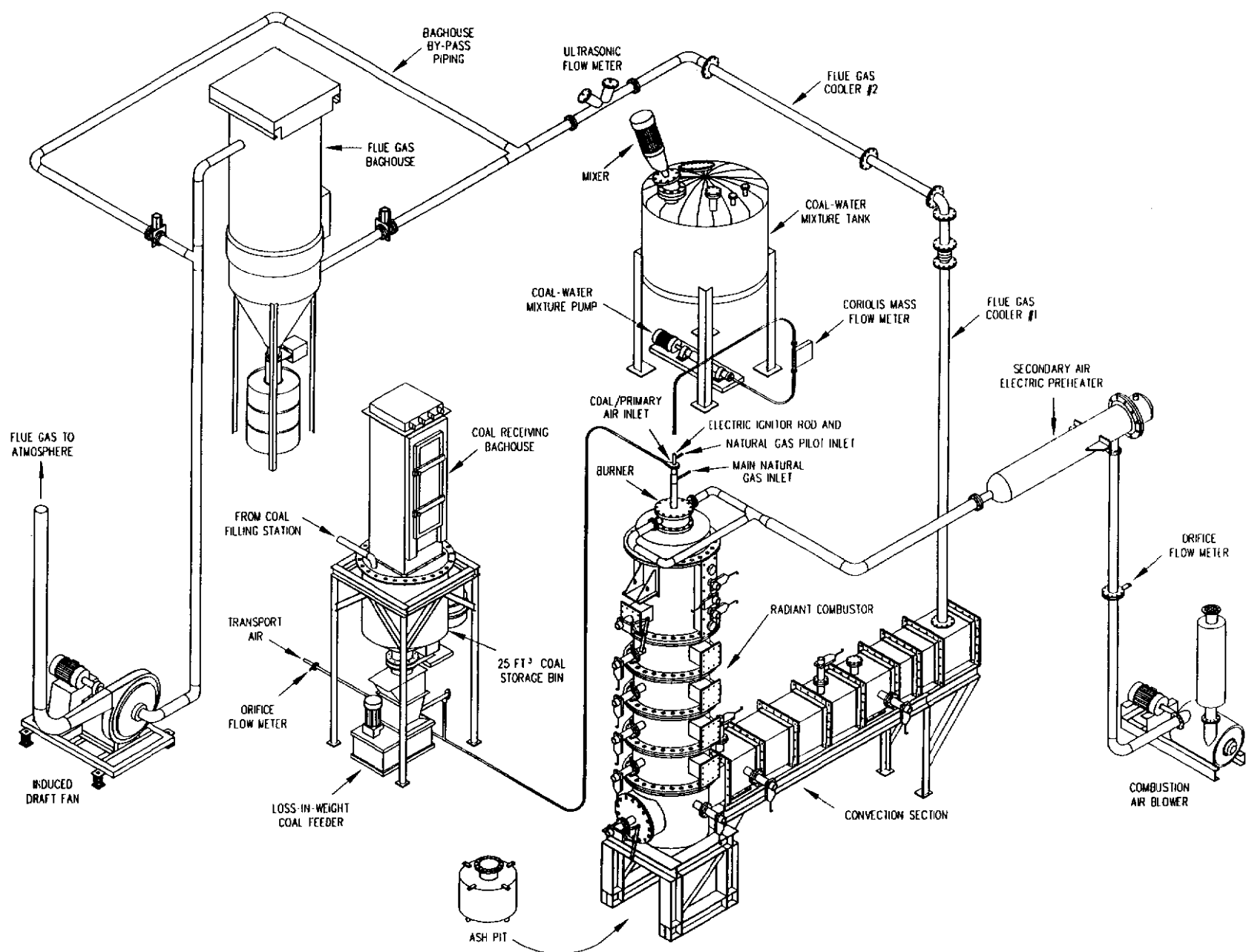
- The Williams Pulverizer tests achieved the desired particle size distributions and moisture content for the GranuFlow products. Post-test inspection revealed only minimal sticking/caking on some of the mill internal components when using GranuFlow products, but this was not judged to potentially cause equipment damage or operational difficulties.
- No problems were encountered with either of the pulverized 20% GranuFlow and 40% GranuFlow products in the CERF's indirect-fired coal feeding/transport system.
- In general, both the 20% and 40% GranuFlow products burned comparably to the parent coal, with only very slight increases ( $< 2$  wt%) in baghouse fly ash LOI in most cases.
- A reduction in early combustion in the CERF's upper furnace, at gas residence times less than 1 second, was observed with both GranuFlow products relative to the parent coal.
- Flue gas emissions of  $\text{SO}_2$ ,  $\text{NO}_x$ , and CO were similar among the GranuFlow products and the parent coal over a wide range of burner conditions.

## References

- (1) "GranuFlow Packages Fine Clean Coal", PETC Review, Issue 12, Winter 1996, Pittsburgh Energy Technology Center, U.S. Department of Energy, pp. 4-8, 1996.
- (2) "Centrifugal Dewatering and Reconstitution of Fine Coal: GranuFlow Process", W.W. Wen and R.P. Killmeyer, Coal Preparation, Volume 17, pp 89-102, 1996.
- (3) "Combined Method for Simultaneously Dewatering and Reconstituting Finely Divided Carbonaceous Materials", W.W. Wen and A.W. Deurbrouck, U.S. Patent No. 4969928, November 13, 1990.
- (4) "Method for Simultaneous Use of a Single Additive for Coal Flotation, Dewatering, and Reconstitution", W.W. Wen, M.L. Gray, and K.J. Champagne, U.S. Patent No. 5379902, January 10, 1995.
- (5) "Centrifugal Dewatering and Reconstitution of Fine Coal: An Industrial Application of GranuFlow Process to Column Flotation Concentrates", W.W. Wen and R.P. Killmeyer, 1997 SME Annual Meeting and Exhibit, preprint number 97-182, Denver, Colorado, February 24-27, 1997.

**Disclaimer**

Reference to specific commercial products, processes, or services is to facilitate understanding and does not imply its endorsement or favoring by the United States Department of Energy.



**Figure 1: Combustion and Environmental Research Facility (CERF)  
of the U.S. DOE Federal Energy Technology Center**